

MeV Dark Matter in the 3+1+1 Model

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Collaboration with Ann E. Nelson

arXiv: 1306.6079

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Outline

- Motivation
- Current Status of Light Sterile Neutrinos
 - Neutrino Experiments
 - Cosmology
- Dark 3+1+1 Model
 - BBN and Supernovae Bounds
- Other implications
 - Dark Matter
 - Explanation of INTEGRAL 511 keV Gamma Line
 - Fermion Mass Hierarchy and Mixings: U(1)' Family Symmetry
 - Baryon Number Asymmetry: Dirac leptogenesis
- Conclusion

Motivation

- LSND + MiniBooNE, reactor antineutrino anomaly, Gallium anomaly indicate one light (\sim eV) sterile neutrino
- 3+1 model disfavored by global fit with null results disappearance neutrino exps.
- The 3+1+1 model constrained by cosmology, collider exps., but viable in MeV region
- Natural MeV dark matter candidate in the 3+1+1 model to explain INTEGRAL
- With additional U(1) family symmetry, all fermion mass hierarchy and mixings can be explained
- Bonus: Dirac leptogenesis to explain Baryon Number Asymmetry

Hints of Sterile Neutrino

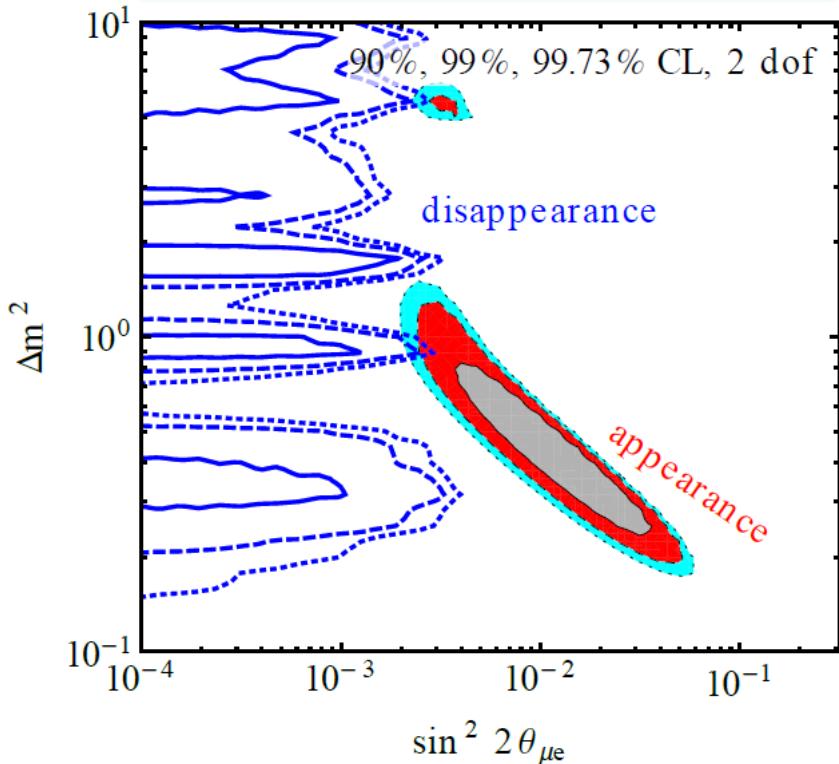
- LSND, MiniBooNE, 3.8σ of \sim eV sterile neutrino
[A. Aguilar-Arevalo et al. \[LSND Collaboration\], PRD 64, 112007 \(2001\)](#)
[A. Aguilar-Arevalo et al. \[MiniBooNE Collaboration\], PRL 98, 231801 \(2007\); PRL 102, 101802 \(2009\); PRL 105, 181801 \(2010\); arXiv:1303.2588](#)
- Reactor Antineutrino Anomaly, 2σ
 $|\Delta m^2_{\text{new}}| > 1.5 \text{ eV}^2$ and $\sin^2(2\theta_{\text{new}}) = 0.14 +/- 0.08$
[Mention, G. et al. Phys. Rev. D 83 \(2011\) 073006](#)
[Huber, Patrick Phys. Rev. C 84 \(2011\) 024617, Erratum-ibid. C85 \(2012\) 029901](#)

Sterile Neutrino Models

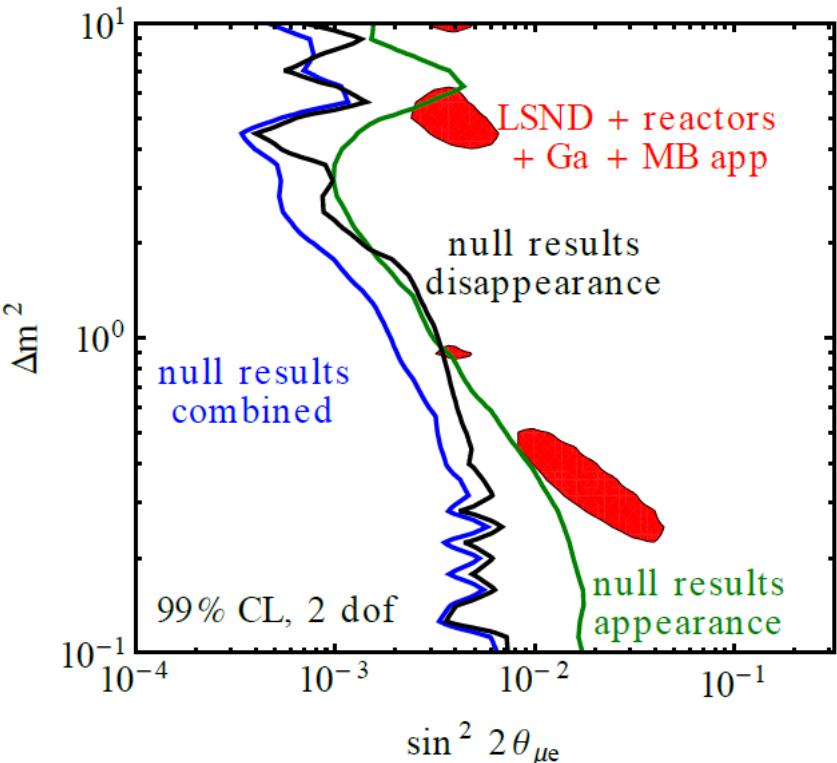
- **3+1 Model:** one additional flavor eV scale sterile neutrino
- **3+2 Model:** two additional flavors eV scale sterile neutrinos, $\Delta m_{41}^2 > 0$ and $\Delta m_{51}^2 > 0$
- **1+3+1 Model:** two additional flavors eV scale sterile neutrinos, $\Delta m_{41}^2 < 0$ or $\Delta m_{51}^2 < 0$
- **3+1+1 Model:** two additional flavors sterile neutrinos, one eV scale and one $33 \text{ eV} \sim 40 \text{ GeV}$ scale
- **3+s ($s > 2$) Model:** more than two additional flavors sterile neutrinos

3+1 Model In Tension

$$\sin^2 2\theta_{\mu e} = 4|U_{e4}|^2 |U_{\mu 4}|^2$$



J. Kopp, et al, JHEP 1305 (2013) 050

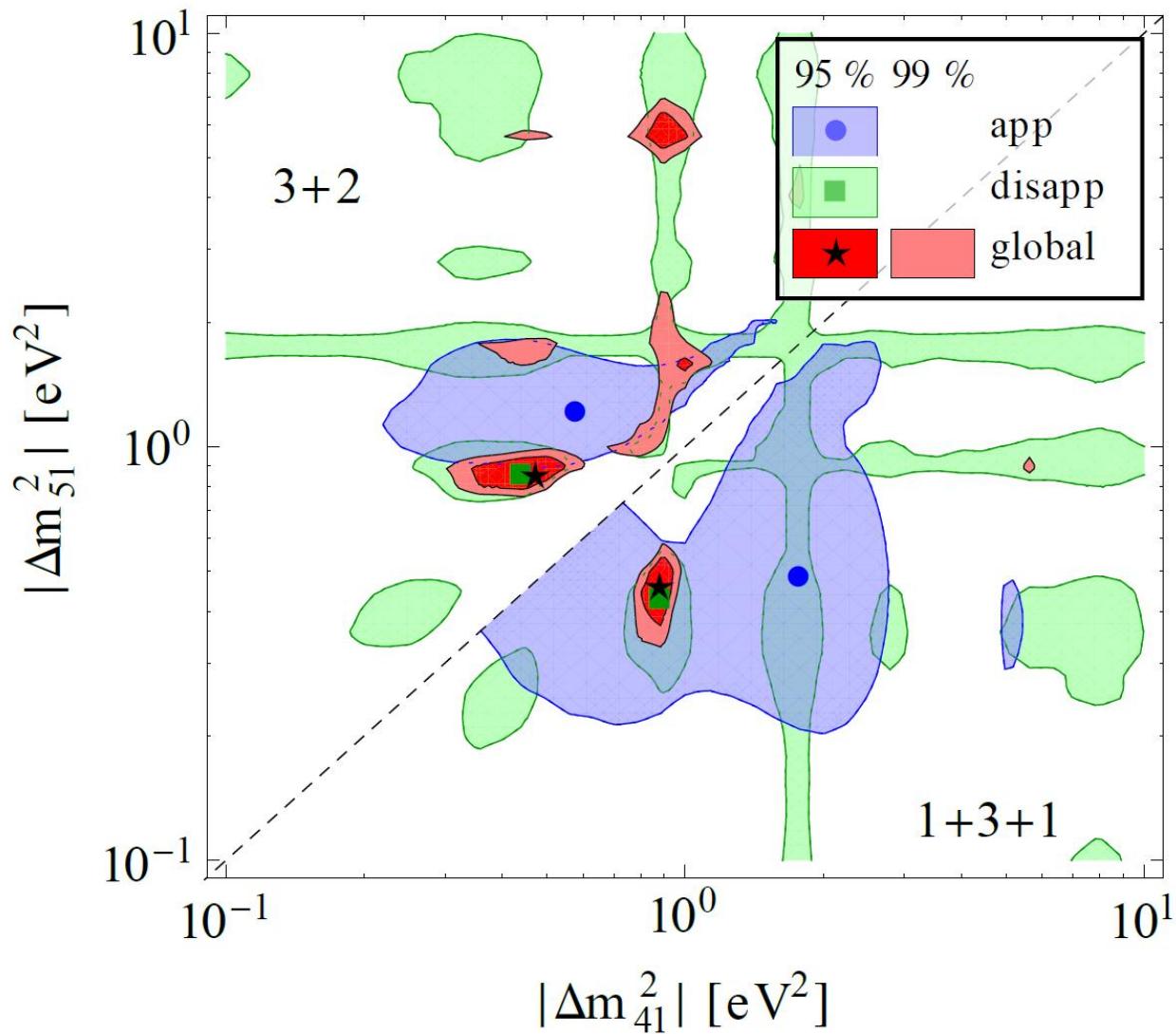


Appearance: LSND, MiniBooNE appearance, NOMAD, KARMEN, ICARUS, E776

Disappearance: atmospheric, solar, reactors, Gallium, CDHS, MINOS, MiniBooNE disappearance, KARMEN, LSND $\nu_e - {}^{12}\text{C}$ scattering

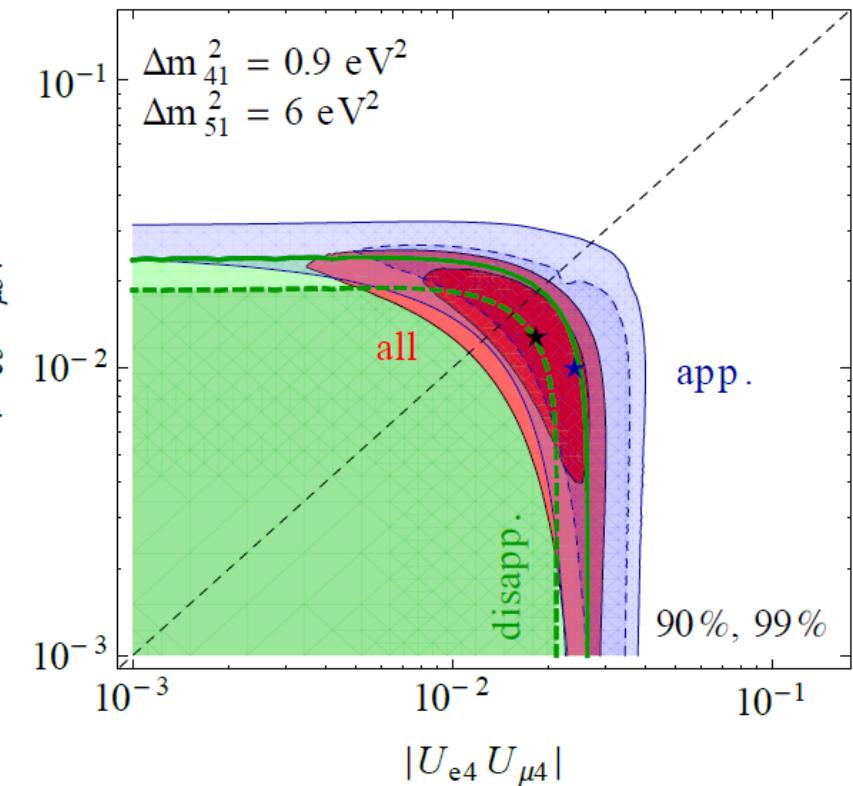
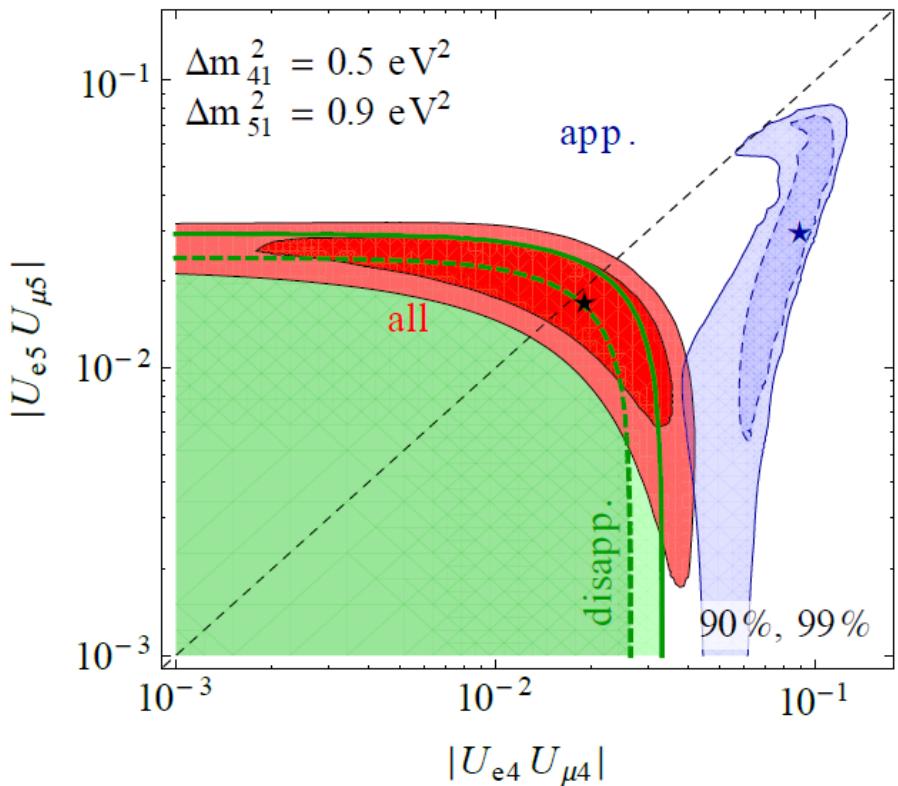
Masses in 3+2 and 1+3+1 Models

J. Kopp, et al, JHEP 1305 (2013) 050



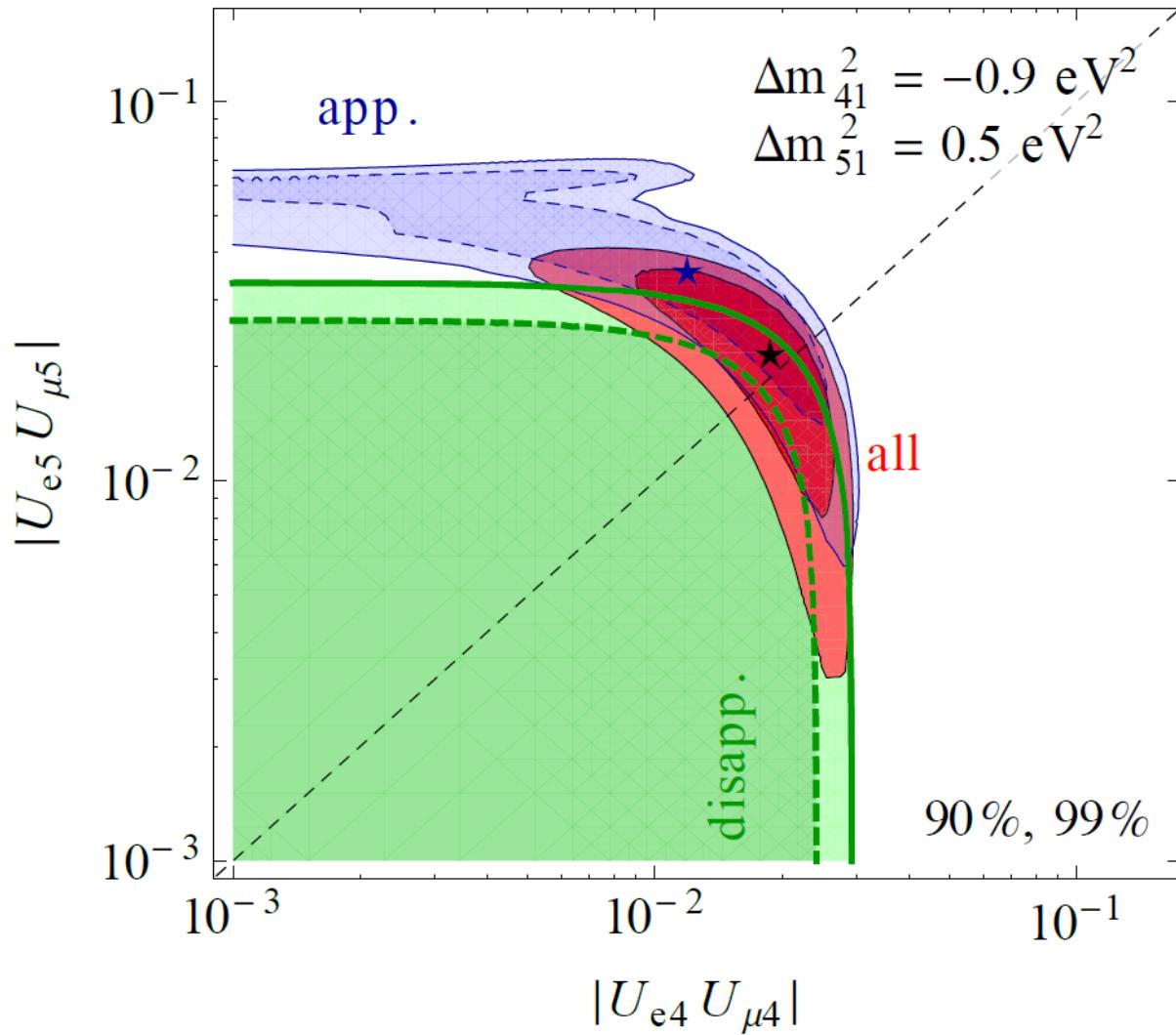
Mixings in 3+2 Model

J. Kopp, et al, JHEP 1305 (2013) 050



Mixings in 1+3+1 Model

J. Kopp, et al, JHEP 1305 (2013) 050



Oscillation Probability in 3+1+1 Model

A. E. Nelson, PRD 84 (2011) 053001

E.Kuflik, S. D. McDermott, K.M.Zurek PRD 86 (2012) 033015

Appearance Probability:

$$P_{\nu_\mu(\bar{\nu}_\mu) \rightarrow \nu_e(\bar{\nu}_e)} = \sin^2 2\theta_{\mu e} \sin^2(x_{41} \pm \beta) + \kappa$$

$$\sin^2 2\theta_{\mu e} = 4|U_{\mu 4}|^2 |U_{e 4}|^2 r \quad x_{ij} = \Delta m_{ij}^2 L / 4E = 1.27 \frac{(m_i^2 - m_j^2)L/E}{\text{eV}^2 \text{m/MeV}}$$

$$r \equiv |U_{\mu 4}^* U_{e 4} + U_{\mu 5}^* U_{e 5}| / |U_{\mu 4}^* U_{e 4}|$$

$$\beta \equiv \frac{1}{2} \tan^{-1} \left(\frac{\sin \phi |U_{e 5}| |U_{\mu 5}|}{|U_{e 4}| |U_{\mu 4}| + \cos \phi |U_{e 5}| |U_{\mu 5}|} \right) \quad \phi \equiv \arg \left(\frac{U_{e 5} U_{\mu 5}^*}{U_{e 4} U_{\mu 4}^*} \right)$$

$$\kappa = |U_{\mu 4}|^2 |U_{e 4}|^2 \{ (1 - r)^2 + a [(1 - r)^2 + 4r \sin^2 \beta] \}$$

Disappearance Probability:

$$1 - P_{\nu_\alpha \rightarrow \nu_\alpha} = \sin^2 2\theta_{\alpha 4} \sin^2 x_{41} + 2|U_{\alpha 5}|^2 \left(1 - \frac{a + 1}{2} |U_{\alpha 5}|^2 \right)$$

$$\sin^2 2\theta_{\alpha 4} = 4|U_{\alpha 4}|^2 (1 - |U_{\alpha 4}|^2 - |U_{\alpha 5}|^2)$$

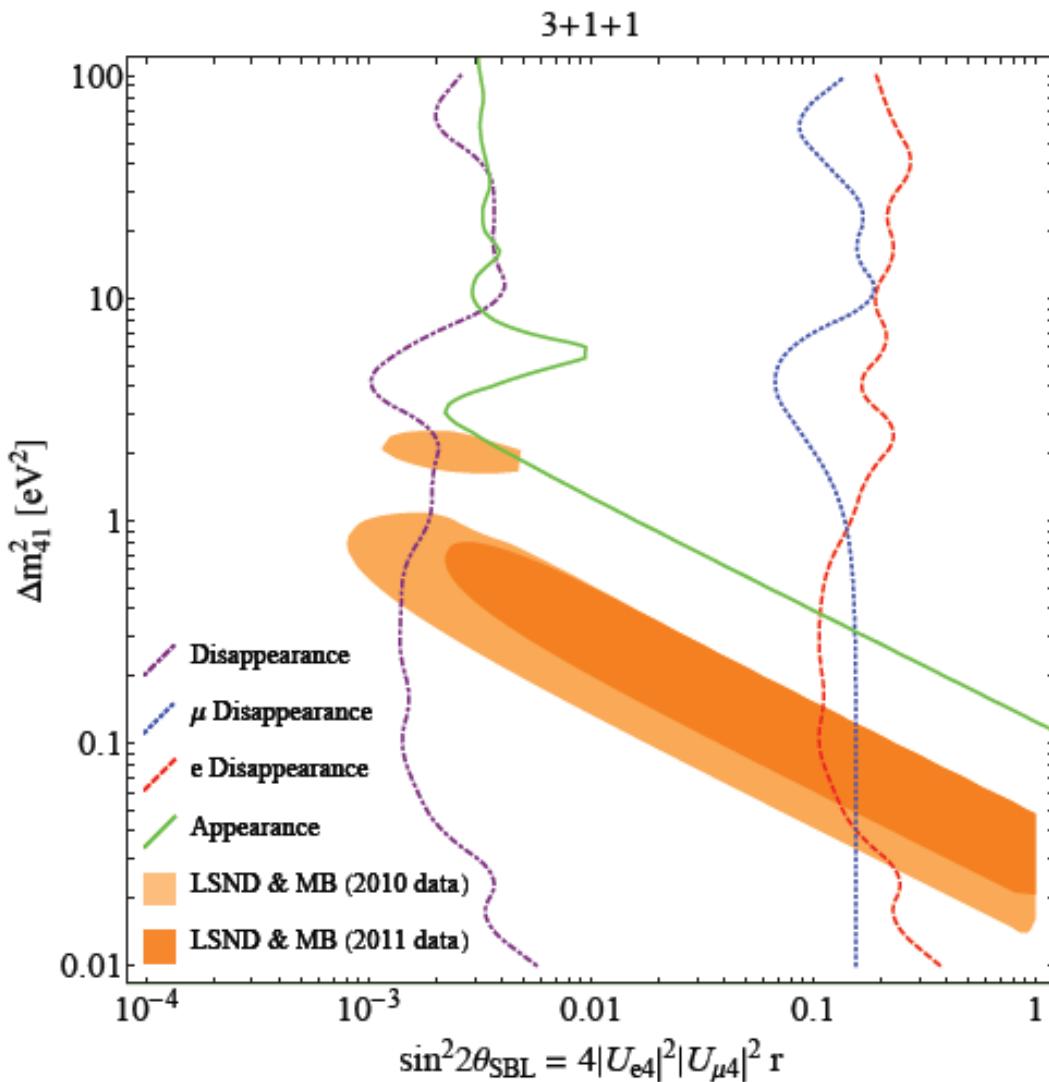
a: phase space parameter associated with ν_5 production

β : CP odd parameter associated with CP violation

In total, 6 free parameters

Fitting in 3+1+1 Model

E.Kuflik, S. D. McDermott, K.M.Zurek PRD 86 (2012) 033015



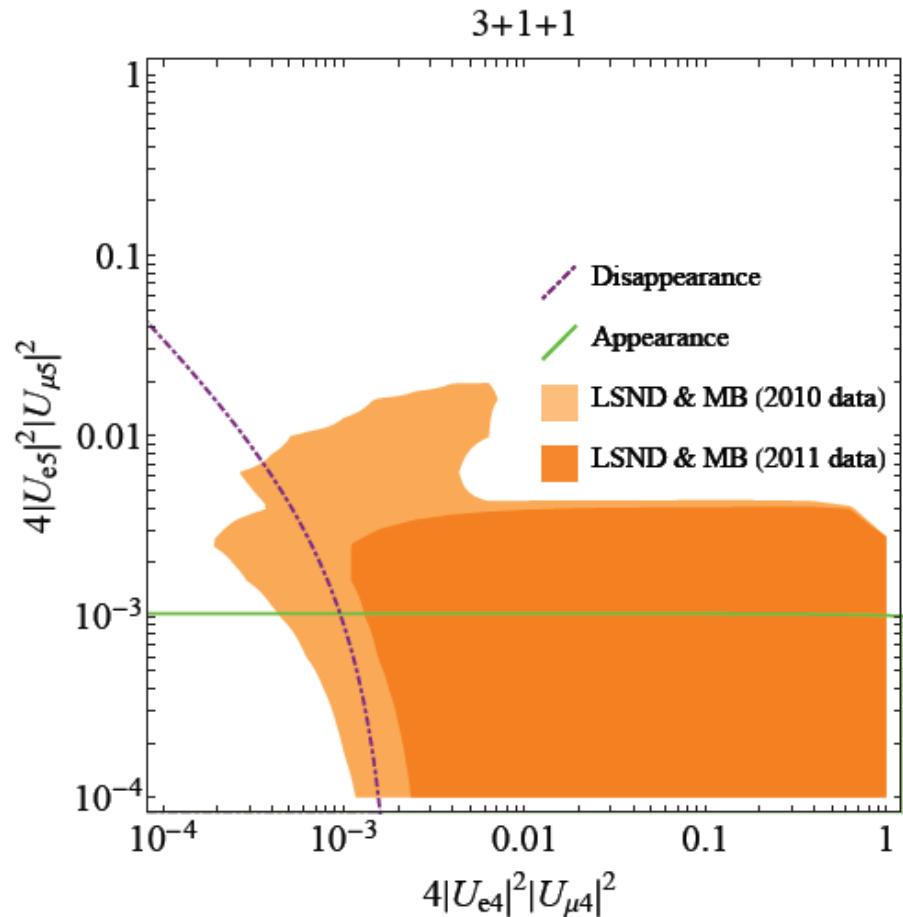
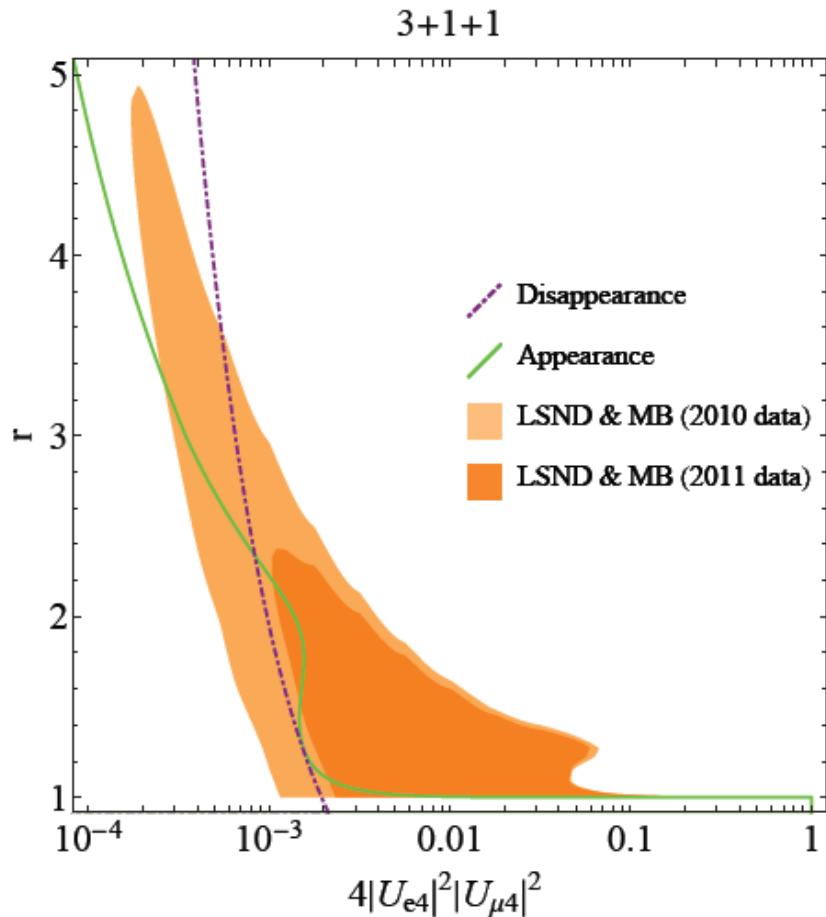
Appearance: KARMEN,
E776, NOMAD, CCFR, NuTeV;

ν_e disappearance: SBL
reactor experiments with
new reactor flux predictions;
ratio of flux observed in the
Bugey 40 m and 15 m detectors;

ν_μ disappearance: CDHS,
CCFR, atmospheric at Super-
Kamiokande.

Fitting in 3+1+1 Model-Cont.

E.Kuflik, S. D. McDermott, K.M.Zurek PRD 86 (2012) 033015



Summary: Sterile Neutrino Models

- 3+1 Model: tension between appearance and disappearance neutrino exps.
- 3+2 Model: allowed, eV scale, $O(0.1)$ mixings
- 1+3+1 Model: allowed, eV scale, $O(0.1)$ mixings
- 3+1+1 Model: allowed, one eV scale, one heavier, $O(0.1)$ mixings
- 3+s ($s > 2$) Model: allowed, no qualitatively difference compared to two sterile neutrino scenarios [M. Maltoni, T. Schwetz, PRD \(2007\) 093005](#)

Dark Radiation

- BBN: [Y. I. Izotov, T. X. Thuan, Astrophys. J. 710, L67 \(2010\)](#)
 - $N_{\text{eff}} = 3.68^{+0.80}_{-0.70}$ (2σ); $N_{\text{eff}} = 3.80^{+0.80}_{-0.70}$ (2σ)
- Nine-year WMAP: [C. L. Bennett et al. \[WMAP Collaboration\], arXiv:1212.5225; arXiv:1212.5226](#)
 - $N_{\text{eff}} > 1.7$ (2σ); $N_{\text{eff}} = 3.84 +/- 0.40$ (1σ) (WMAP + ACT+SPT + BAO + H_0)
- High resolution ground-base CMB experiments:
 - Atacama Cosmology Telescope (ACT)
 - $N_{\text{eff}} = 2.79 +/- 0.56$ (2σ) [J. L. Sievers et al., arXiv:1301.0824](#)
 - South Pole Telescope (SPT)
 - $N_{\text{eff}} = 3.71 +/- 0.35$ (1.9σ) (SPT+WMAP7+ H_0 +BAO) [S. Zhou, arXiv:1212.6267](#)

PLANCK

P. A. R. Ade et al. [Planck Collaboration], arXiv:1303.5076

- Combine Planck, nine-year WMAP, Baryon Acoustic Oscillations (BAO), ACT, SPT:

$$N_{\text{eff}} = 3.30^{+0.54}_{-0.51} \text{ (2 } \sigma\text{)}$$

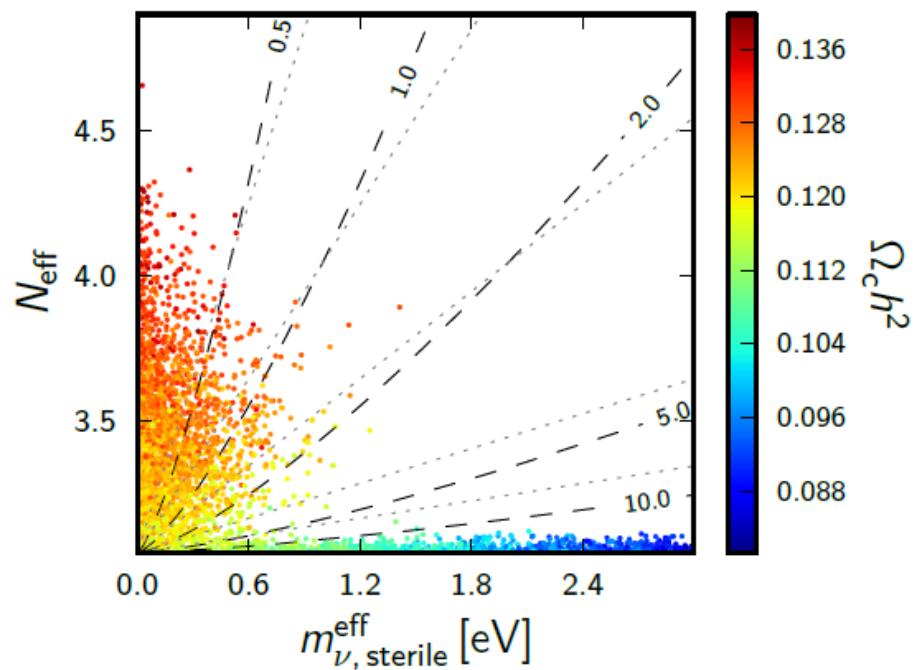
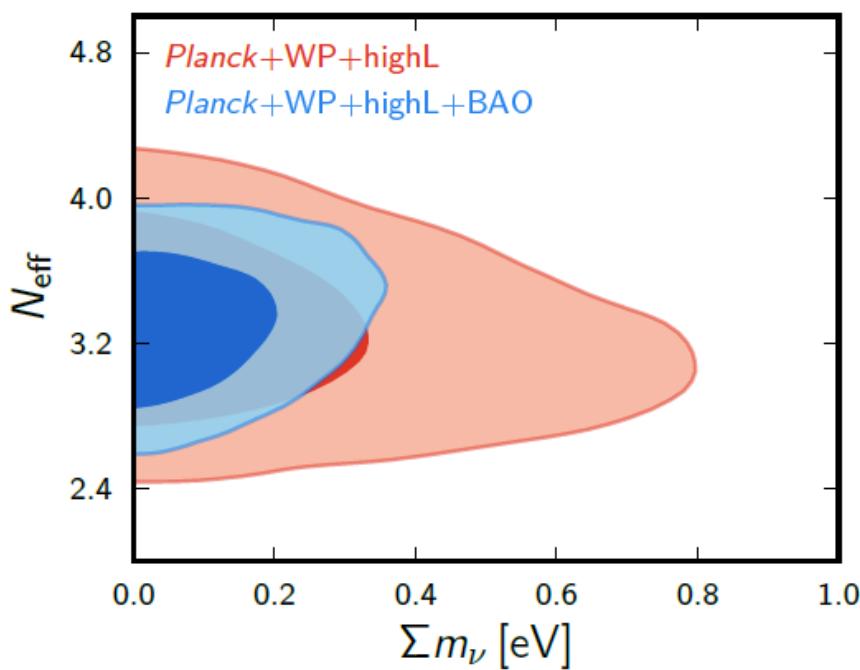
- Include additional direct measurements of the Hubble Constant H_0 :

$$N_{\text{eff}} = 3.52^{+0.48}_{-0.45} \text{ (2 } \sigma\text{)}$$

Planck Result on Sterile Neutrino

Planck Collaboration, arXiv:1303.5076

There is still room for one sub-eV sterile neutrino (~ 0.6 eV).



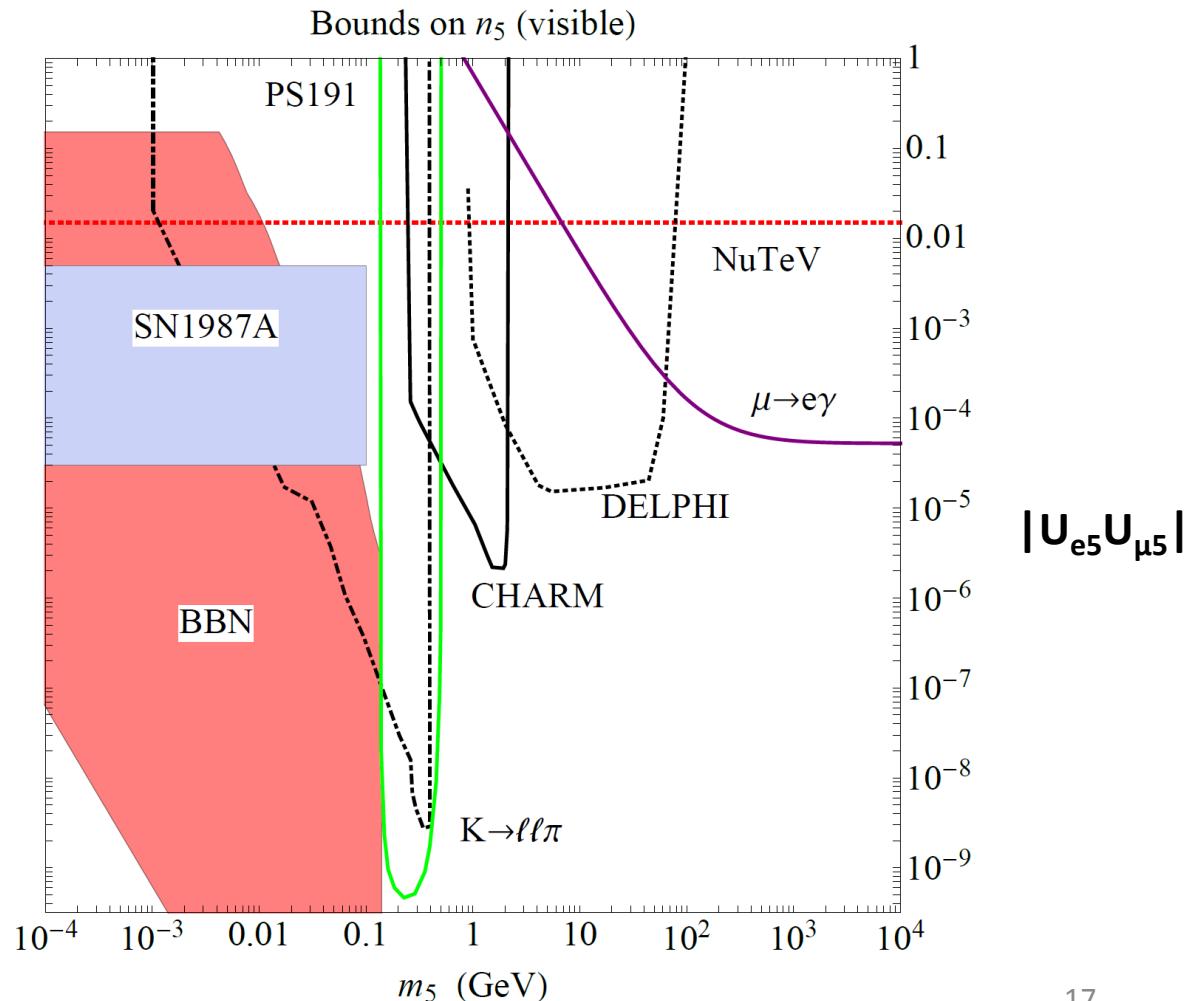
More Constraints on 3+1+1 Model

E.Kuflik, S. D. McDermott, K.M.Zurek PRD 86 (2012) 033015

Hierarchical: $\nu_{s1} \sim \text{eV}$,
 $\nu_{s2} \sim [33\text{eV}, 10\text{GeV}]$

Mixing: $\theta \sim O(0.1)$ for
LSND, MiniBooNE

Ruled out by exps.

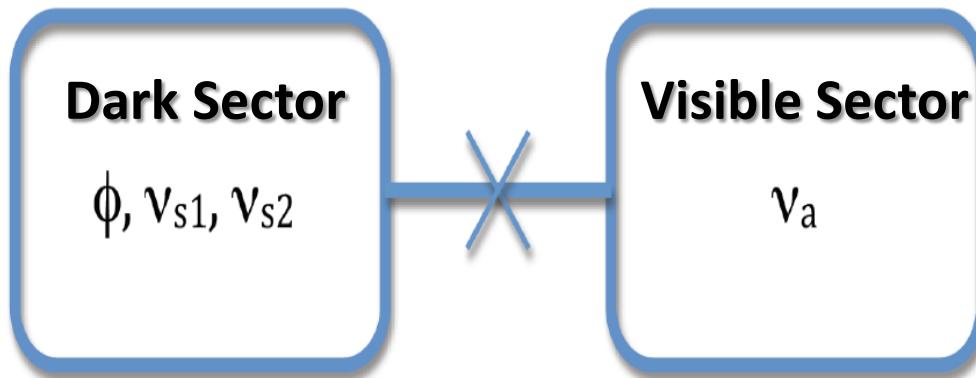


Dark 3+1+1 Model

JH, A E Nelson arXiv: 1306.6079

Introduce additional ϕ field and new interaction

$$\mathcal{L}_\phi = \lambda \phi \nu_{s1} \nu_{s2} + h.c.$$



v_{s1} : subeV \sim eV sterile neutrino
 v_{s2} : [1,34]MeV sterile neutrino
 ϕ : [1,7]MeV scalar
 v_a : active neutrino

X: Mixing between active and sterile neutrinos;
Particles in Dark Sector scatter among themselves.

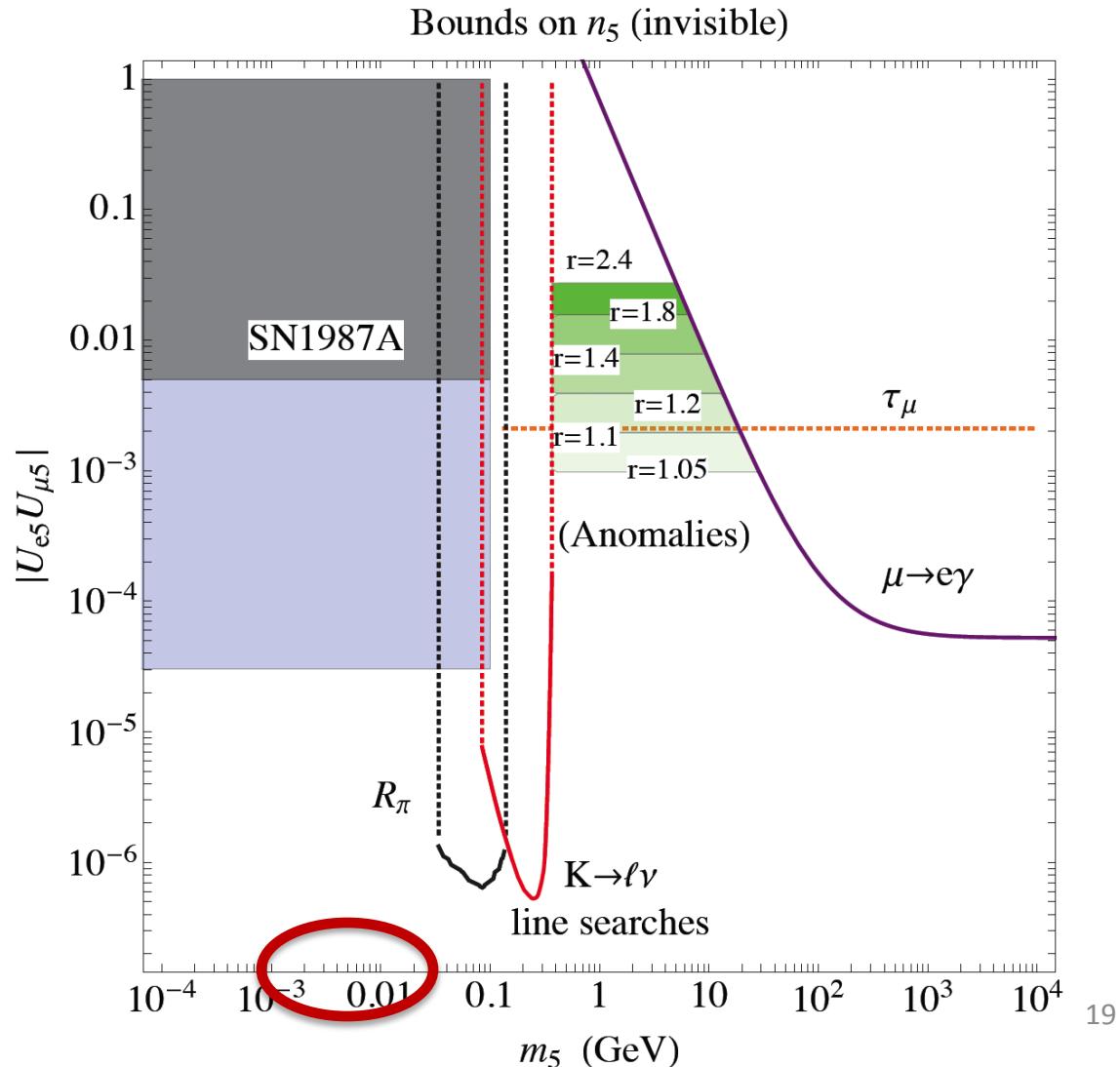
Lead to invisible decay $\nu_5 \rightarrow \nu_4 \phi$, $\Gamma^{\text{inv}}_{\nu 5} \approx \lambda^2 m_5 / (16\pi)$

Constraints on Dark 3+1+1 Model

E. Kuflik, S. D. McDermott, K.M.Zurek PRD86 (2012) 033015

SN1987A, BBN
controlled
region can be
open up

MeV ϕ field:
dark matter
candidate;
explain 511keV
INTEGRAL



BBN Constraint on Dark 3+1+1 Model

A. D. Dolgov, S. H. Hansen, G. Raelt D. V. Semikoz, Nucl. Phys. B 590, 562 (2000);
A. D. Dolgov, F. L. Villante, Nucl. Phys. B 679, 261 (2004);
O. Ruchayskiy, A. Ivashko, JCAP 1210, 014 (2012)

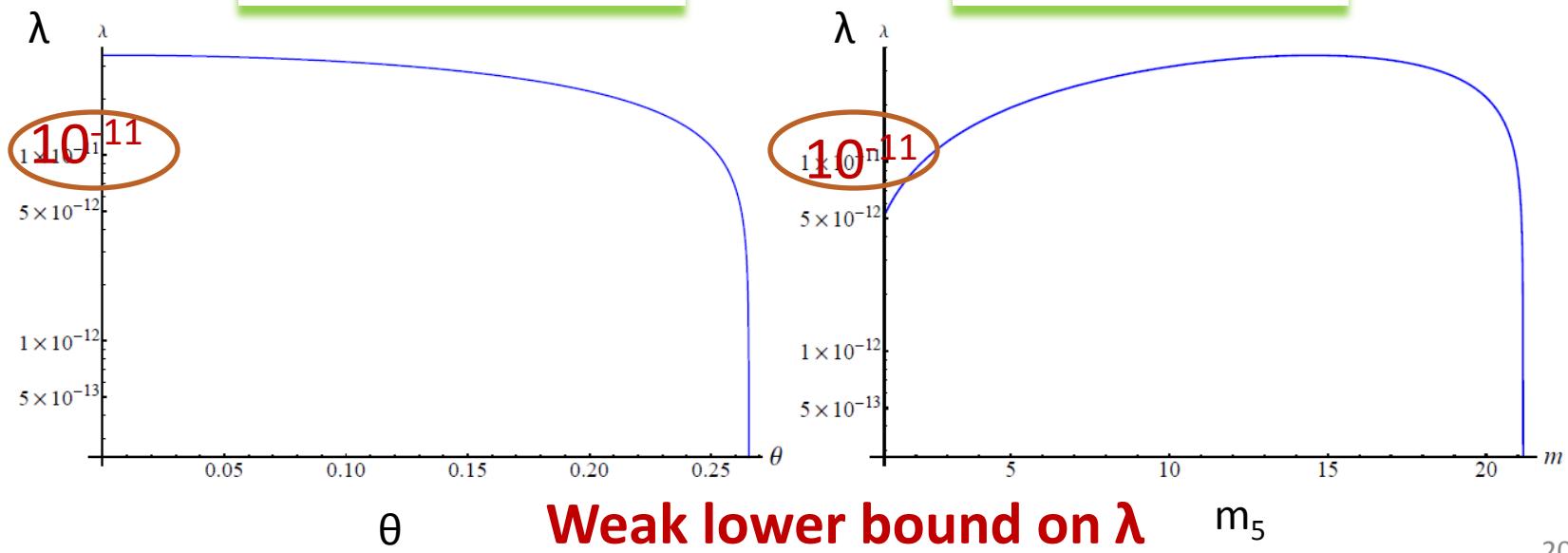
$\nu_5 \rightarrow \nu_a e^+ e^-$ decay modifies the Helium abundance:

short lifetime avoid the bound:

$$\frac{\hbar}{\Gamma_{\nu_5}^{\text{inv}} + \Gamma_{\nu_5}^{\text{ee}}} < t_1 \left(\frac{m_5}{\text{MeV}} \right)^\beta + t_2$$

$$\Gamma_{\nu_5}^{\text{ee}} \simeq \frac{\left(\frac{m_5}{10\text{MeV}} \right)^5 s_{2\theta_{e5}}^2 \hbar}{0.7}$$

$$\Gamma_{\nu_5}^{\text{inv}} \simeq \frac{1}{16\pi} \lambda^2 m_5$$

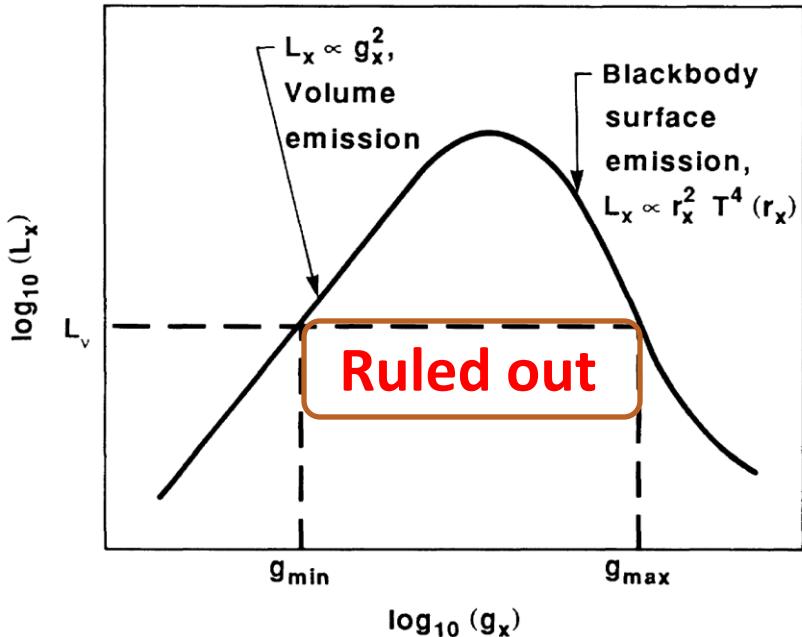


SN1987a Constraint-I

G. Raelt, D. Seckel, PRL 60, 1793

K. Kainulainen, J. Maalampi, J. T. Peltoniemi,
Nucl. Phys. B 358, 435

In general, require new particle:
 1) well trapped inside the supernovae:
 interaction length $l_{v5} \leq 1.5$ m;
 Or 2) escape the supernovae:
 interaction length $l_{v5} \geq 4.6 \times 10^4$ km



$v_5 v_4 \phi$: well trapped inside the supernovae core

$$\Gamma_\phi \geq \Gamma_{\text{van}} \quad \rightarrow \quad n_\nu \frac{(\lambda^\nu)^4}{\langle E \rangle^2} \gtrsim n_N \frac{1}{2} \sin^2 2\theta_m G_F^2 \langle E \rangle^2 \Big|_{(\sin^2 2\theta_m = 2 \times 10^{-2})}$$

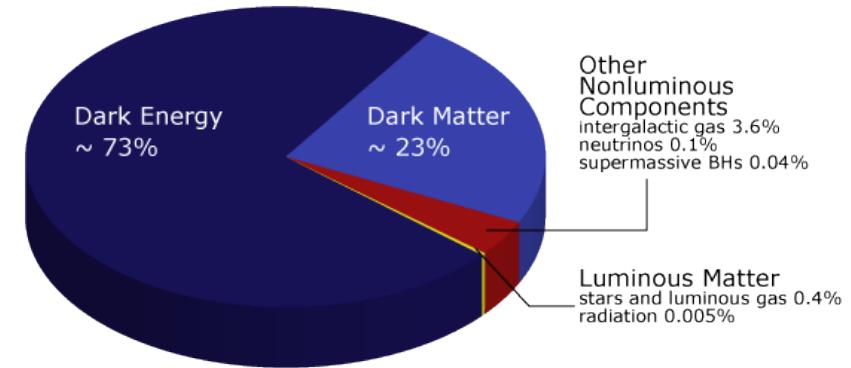
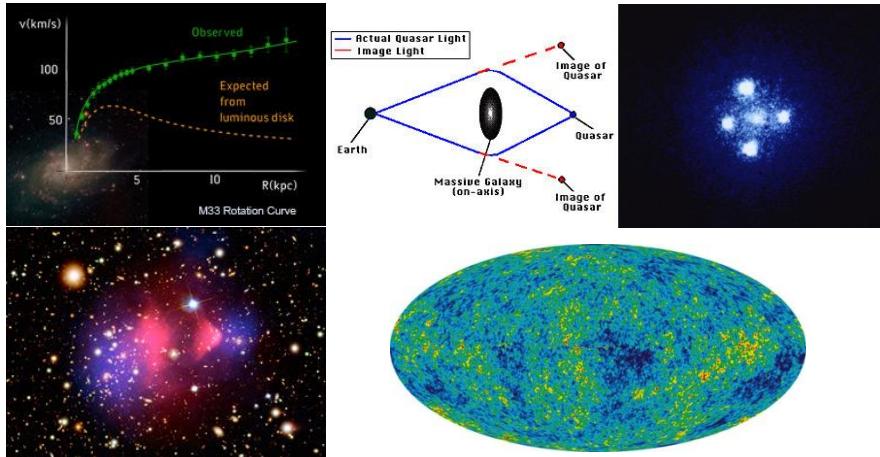
SN1987a Constraint-II

Interaction between dark sector/visible sector modifies active neutrino mean free path, needs weaker than EW interaction.

$$\Gamma_{\phi \text{ va}} \leq \Gamma_{EW} \quad \xrightarrow{\text{orange arrow}} \quad \left(\frac{1}{2} \sin^2 2\theta_m \right)^2 n_\nu \frac{(\lambda^\nu)^4}{\langle E \rangle^2} \leq n_N G_F^2 \langle E \rangle^2$$

$$2 \times 10^{-4} \lesssim \lambda^\nu \lesssim 0.5 \times 10^{-2}$$

Dark Matter



Evidences of DM:

- Motion of Galaxy
- Structure simulations
- Temperature fluctuations in CMB
- Gravitational lensing
- Cooling clusters

Properties of DM:

- Not Luminous
- Long Lived
- Not Hot
- Not dissipative

Neutrinophilic MeV DM

- No confirmed signals of DM yet;
- Current DM direct detections not sensitive to MeV region;
- Detections assume DM interacting with quarks;
- Light MeV DM or neutrinophilic DM:
 - NOT covered in the current DM detection experiments.

Constraints on Neutrinophilic MeV DM from Supernovae

P. Fayet, D. Hooper , G. Sigl, PRL 96, 211302 (2006)

- cross section of DM annihilating into active neutrinos

$\sim 10^4$ **stronger** than the weak interaction

→ interaction length of the active neutrino too short;
ruled out by Supernovae SN1987a

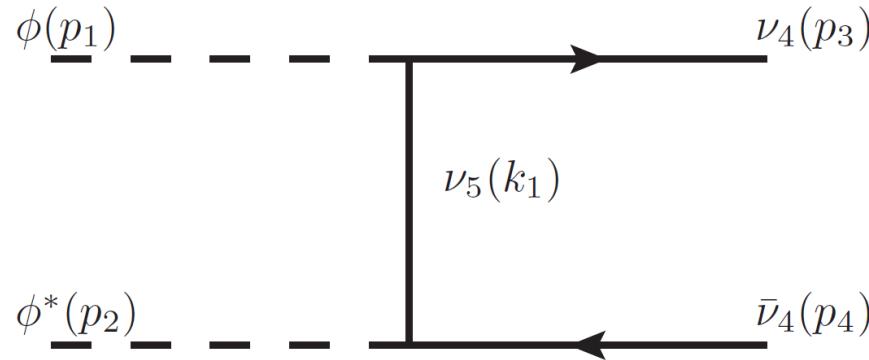
[1, 30] MeV DM region ruled out.

- In dark 3+1+1 Model, DM annihilates into sterile neutrino pairs dominantly,

→ cross section of the DM annihilation into active neutrino pairs **suppressed** by the mixing angles 10^{-4}
Avoid the supernovae bound.

DM Relic Abundance

DM annihilates into sterile neutrino pair



$$\sigma_{\text{ann}} v_{\text{rel}} = \frac{\lambda^4}{4\pi} \frac{m_5^2}{(m_\phi^2 + m_5^2)^2} \simeq 0.3 \left(\frac{\lambda}{10^{-3}} \right)^4 \left(\frac{10 \text{ MeV}}{m_5} \right)^2 \text{ pb}$$

For right relic abundance, $\sigma_{\text{ann}} v_{\text{rel}} \simeq 0.2 \times \frac{x_F}{\sqrt{g_*}} \left(\frac{\Omega_{dm} h^2}{0.11} \right)^{-1} \text{ pb}$



$$\lambda \sim 3 \times 10^{-4} - 2 \times 10^{-3}$$

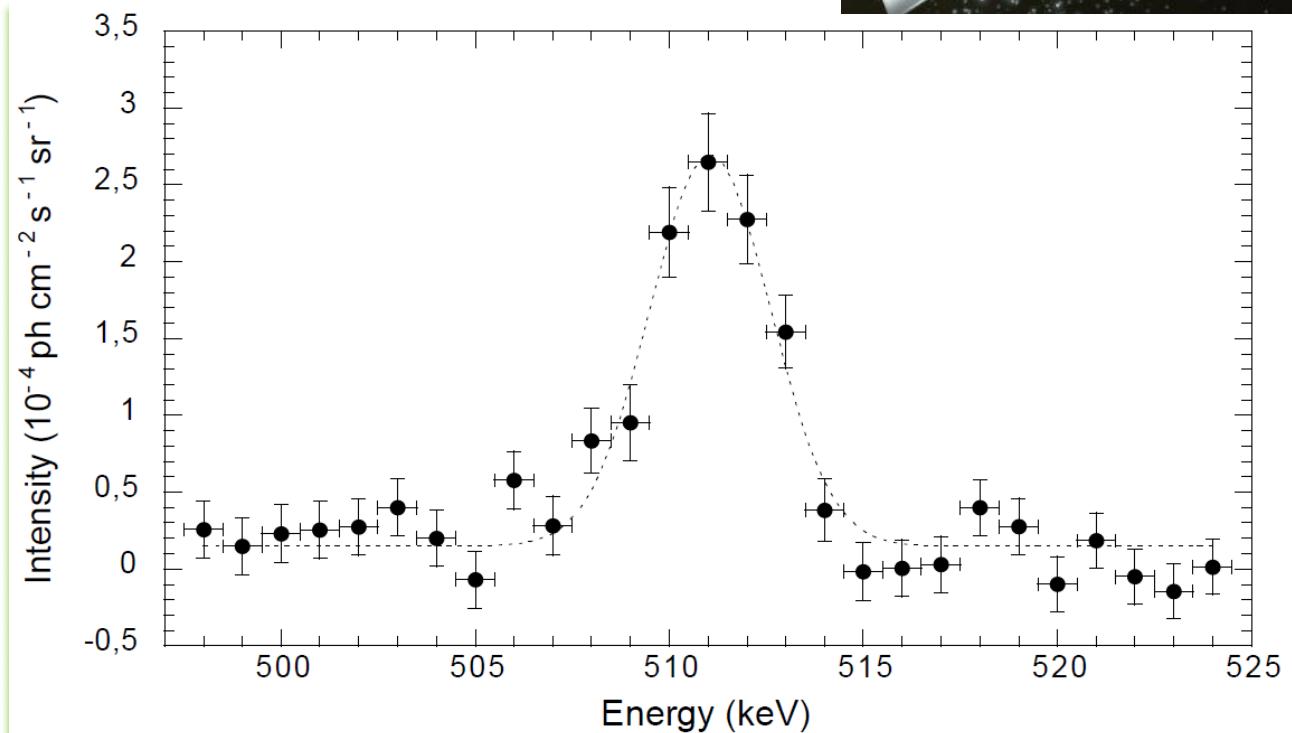
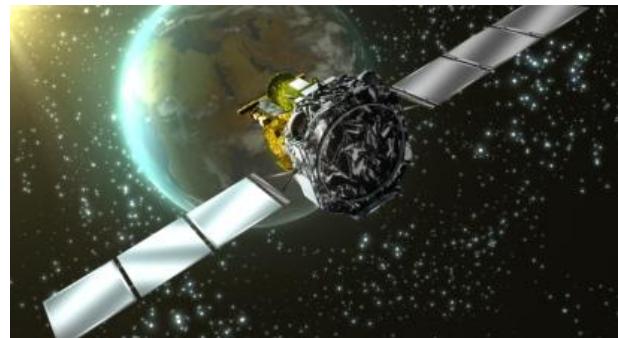
511 keV INTEGRAL Gamma-Ray Line

P. Jean et al, Astron.Astrophys.407:L55,2003

Flux: $9.9^{+4.7}_{-2.1} \times 10^{-4}$ ph cm $^{-2}$ s $^{-1}$

Centroid: $511.06^{+0.17}_{-0.19}$

Width: $2.95^{+0.45}_{-0.51}$ keV (FWHM)



MeV DM and 511 keV INTEGRAL

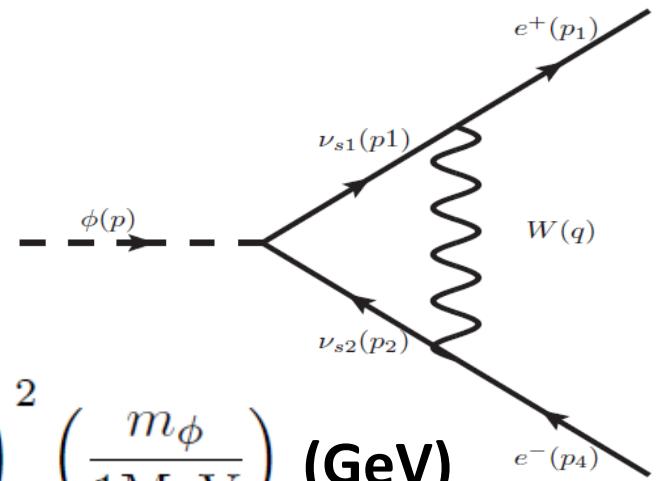
- DM annihilation into electron pair:
C. Boehm, P. Fayet, Nucl. Phys. B 683, 219 (2004);
C. Boehm, et al, PRL 92, 101301 (2004)
- DM decay into electron pair:
C. Picciotto, M. Pospelov, PLB 605, 15 (2005)
M. Pospelov, A. Ritz, PLB 651, 208 (2007)
- Excited DM with MeV mass splitting:
M. Pospelov, A. Ritz, PLB 651, 208 (2007);
D. P. Finkbeiner, N. Weiner, PRD 76, 083519 (2007);
N. Arkani-Hamed, D. P. Finkbeiner, T. R. Slatyer, N. Weiner, PRD79 (2009) 015014;
J. M. Cline, A. R. Frey, F. Chen, PRD 83, 083511 (2011);
Y. Bai, M. Su, Y. Zhao, JHEP 1302, 097 (2013)

INTEGRAL Constraints on DM Models

- To fit the continuum photon energy spectrum of 511 keV INTEGRAL gamma line:
 - $m_{DM} < 30 \text{ MeV}$ [N. Prantzos et al., arXiv:1009.4620](#)
- Avoid Internal Bremsstrahlung with positron production violating the COMPTEL and EGRET diffuse gamma-ray observation:
 - $m_{DM} < 20 \text{ MeV}$ [J. F. Beacom, N. F. Bell, G. Bertone, PRL 94, 171301 \(2005\)](#)
- DM annihilating into electron pair through new interaction can modify the fine structure constant:
 - $m_{DM} < 7 \text{ MeV}$ [C. Boehm, Y. Ascasibar, PRD 70, 115013](#)
- Be consistent with the diffuse Galactic gamma-ray data
 - Positron injection energy $< 3 \text{ MeV}$ [J. F. Beacom, H. Yuksel, PRL 97, 071102 \(2006\)](#)

Explain INTEGRAL in Dark 3+1+1 Model

DM decay into electron pair



$$\Gamma_{\phi \rightarrow e^+ e^-} \simeq 10^{-50} \left(\frac{\lambda}{10^{-3}} \cdot \frac{|U_{s15}|}{10^{-7}} \cdot \frac{m_5}{10\text{MeV}} \right)^2 \left(\frac{m_\phi}{1\text{MeV}} \right) \text{(GeV)}$$

$$|U_{e5}^* U_{e5}|^2 \simeq 10^{-4} \quad |U_{s25}|^2 \simeq 1 \quad \text{have been applied}$$

Explain INTEGRAL: $\tau_\phi \sim 10^{18}$ years

$$\left(\frac{\lambda}{10^{-3}} \cdot \frac{|U_{s15}|}{10^{-7}} \cdot \frac{m_5}{10\text{MeV}} \right)^2 \left(\frac{m_\phi}{1\text{MeV}} \right) \sim \mathcal{O}(1)$$

Explain INTEGRAL in Dark 3+1+1 Model-Cont.

DM decay into neutrino pair

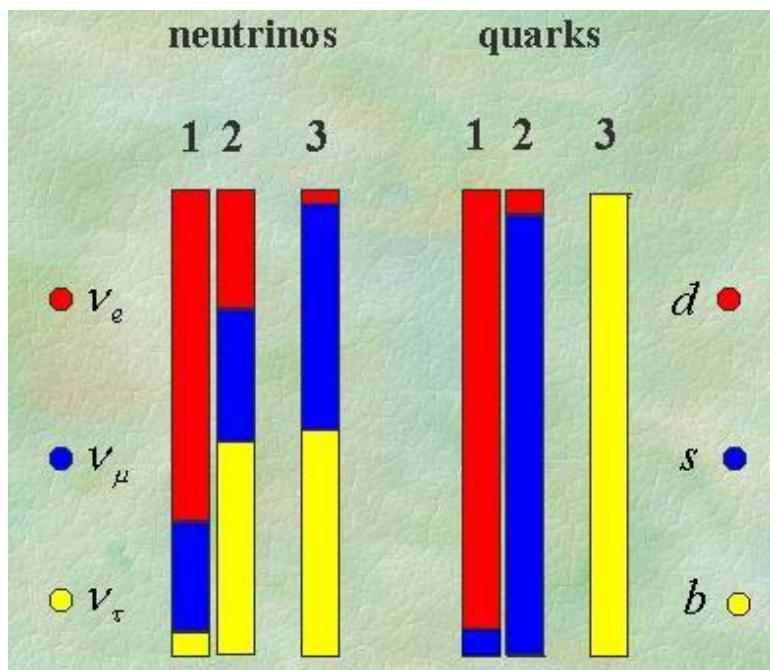
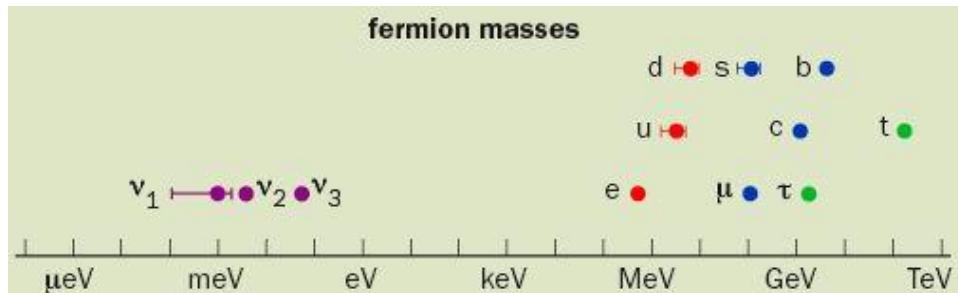
$$\Gamma_{\nu\nu} \simeq 10^{-50} \left(\frac{|U_{s1i} U_{s2i}^*|}{10^{-20}} \right)^2 \left(\frac{\lambda}{10^{-3}} \right)^2 \left(\frac{m_\phi}{\text{MeV}} \right) \text{ (GeV)}$$
$$(i = 1, 2, 3, 4)$$

Highly suppressed to explain INTEGRAL

$$|U_{s1i} U_{s2i}^*| < 10^{-20} \text{ for } \lambda \simeq 10^{-3} \text{ and } m_\phi \sim \text{MeV}$$

Fermion Masses, Mixings

P. Ramond, R. G. Roberts, G. G. Ross, Nucl. Phys. B406 (1993) 19



$$m_b : m_s : m_d \cong 1 : \lambda^2 : \lambda^4$$

$$m_\tau : m_\mu : m_e \cong 1 : \lambda^2 : \lambda^4$$

$$m_t : m_c : m_u \cong 1 : \lambda^4 : \lambda^8$$

Cabbibo angle: $\lambda \cong 0.22$

$$m_{\nu_2}^2 - m_{\nu_1}^2 = 7.58 \times 10^{-5} \text{ eV}^2$$

$$|m_{\nu_3}^2 - m_{\nu_1}^2| = 2.35 \times 10^{-3} \text{ eV}^2$$

$$m_4 \sim \text{sub-eV}$$

$$m_5 \sim \text{MeV}$$

Quark sector: CKM matrix
small mixing;

Lepton sector: PMNS matrix
large mixing.

Models to Explain Fermion Masses, Mixings

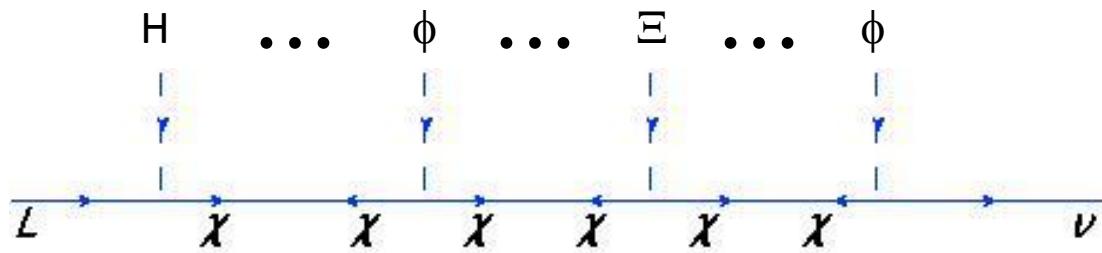
- Family Symmetries
 - Continuous Symmetry
 - $U(1)$, $SU(2)$, $SU(3)$ etc
 - Discrete Symmetry
 - A_4 , T' , A_5 , S_4 etc
- To explain small neutrino masses,
 - popular approach: seesaw mechanism
- In Dark 3+1+1 Model, all fermions are Dirac Particles,
 - no canonical seesaw mechanism,
 - one natural approach: higher dimensional operators with $U(1)'$ symmetry

Froggatt-Nielsen Mechanism

D. D. Froggatt, H. B. Nielsen, Nucl. Phys. B147, 277 (1979)

$$L_{Yukawa} = Y_u Q u H_1 + Y_d Q d \bar{H}_2 + Y_e L e \bar{H}_2 + Y_\nu L \nu H_1 \Xi$$

Froggatt Nielsen Mechanism



$$Y_{ij} \sim (y_{ij} \frac{\phi}{\Lambda})^{|q_i + q_j + q_H|}$$

$$\frac{\langle \Xi \rangle}{\Lambda} \sim O(1)$$

$$\lambda = \frac{\langle \phi \rangle}{\Lambda} \cong 0.22$$

(Cabibbo Angle)

- Effective Yukawa matrices depend on the U(1)' charge assignment.
- $\Xi \xi \chi \chi$ play important roles in Dirac letogenesis.

U(1)' Charges

| Field | $U(1)'$ charge | Field | $U(1)'$ charge |
|----------------------|-------------------|-----------------|-------------------|
| $\bar{\mathbf{5}}_1$ | $q_{f_1} = -13/3$ | $\mathbf{10}_1$ | $q_{t_1} = 3$ |
| $\bar{\mathbf{5}}_2$ | $q_{f_2} = -16/3$ | $\mathbf{10}_2$ | $q_{t_2} = 2$ |
| $\bar{\mathbf{5}}_3$ | $q_{f_3} = -16/3$ | $\mathbf{10}_3$ | $q_{t_3} = 0$ |
| ν_{n_1} | $q_{n_1} = 28/3$ | ν_{r_1} | $q_{r_1} = 0$ |
| ν_{n_2} | $q_{n_2} = 25/3$ | ν_{r_2} | $q_{r_2} = -17/2$ |
| ν_{n_3} | $q_{n_3} = 25/3$ | ν_{l_1} | $q_{l_1} = 9/2$ |
| η | $q_\eta = -1$ | ν_{l_2} | $q_{l_2} = 5$ |
| H_1 | $q_{H_1} = 0$ | Ξ | $q_\Xi = 17$ |
| H_2 | $q_{H_2} = -22/3$ | χ | $q_\chi = 7/2$ |

Mass Matrices

Up-type Quark

$$M^u \sim \begin{pmatrix} \epsilon^6 & \epsilon^5 & \epsilon^3 \\ \epsilon^5 & \epsilon^4 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & \epsilon^0 \end{pmatrix} \langle H_1 \rangle$$

Down-type Quark

$$M^d \simeq \begin{pmatrix} \epsilon^6 & \epsilon^5 & \epsilon^5 \\ \epsilon^5 & \epsilon^4 & \epsilon^4 \\ \epsilon^3 & \epsilon^2 & \epsilon^2 \end{pmatrix} \langle H_2 \rangle$$

Charged Lepton

$$M^e \simeq (M^d)^T$$

SU(5) embed

Active Neutrino

$$M^{an} \simeq \begin{pmatrix} \epsilon^{22} & \epsilon^{21} & \epsilon^{21} \\ \epsilon^{21} & \epsilon^{20} & \epsilon^{20} \\ \epsilon^{21} & \epsilon^{20} & \epsilon^{20} \end{pmatrix} \langle H_1 \rangle$$

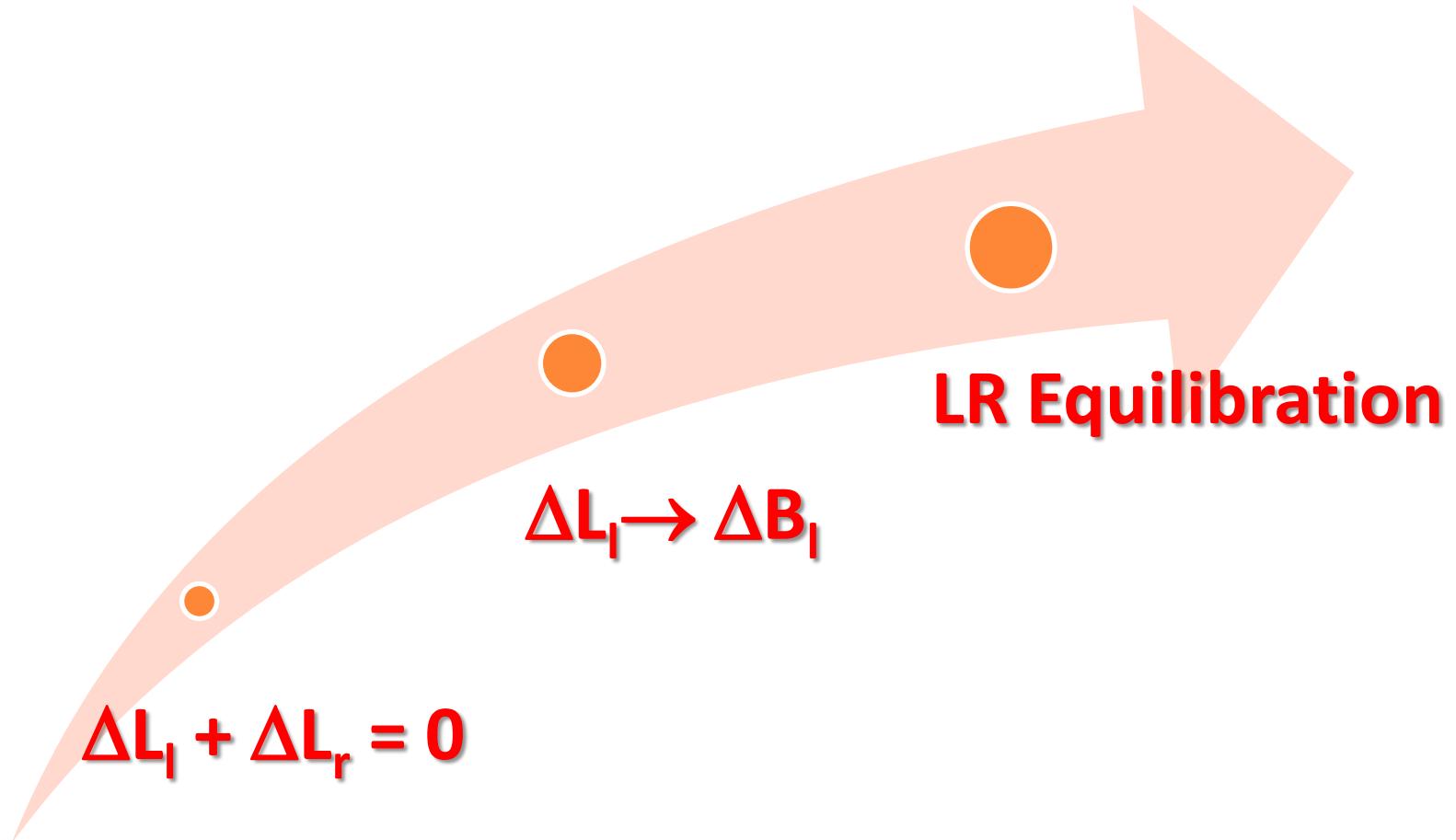
Sterile Neutrino

$$M^{lr} \simeq \begin{pmatrix} \epsilon^8 & 0 \\ 0 & 1 \end{pmatrix} \langle \chi \rangle$$

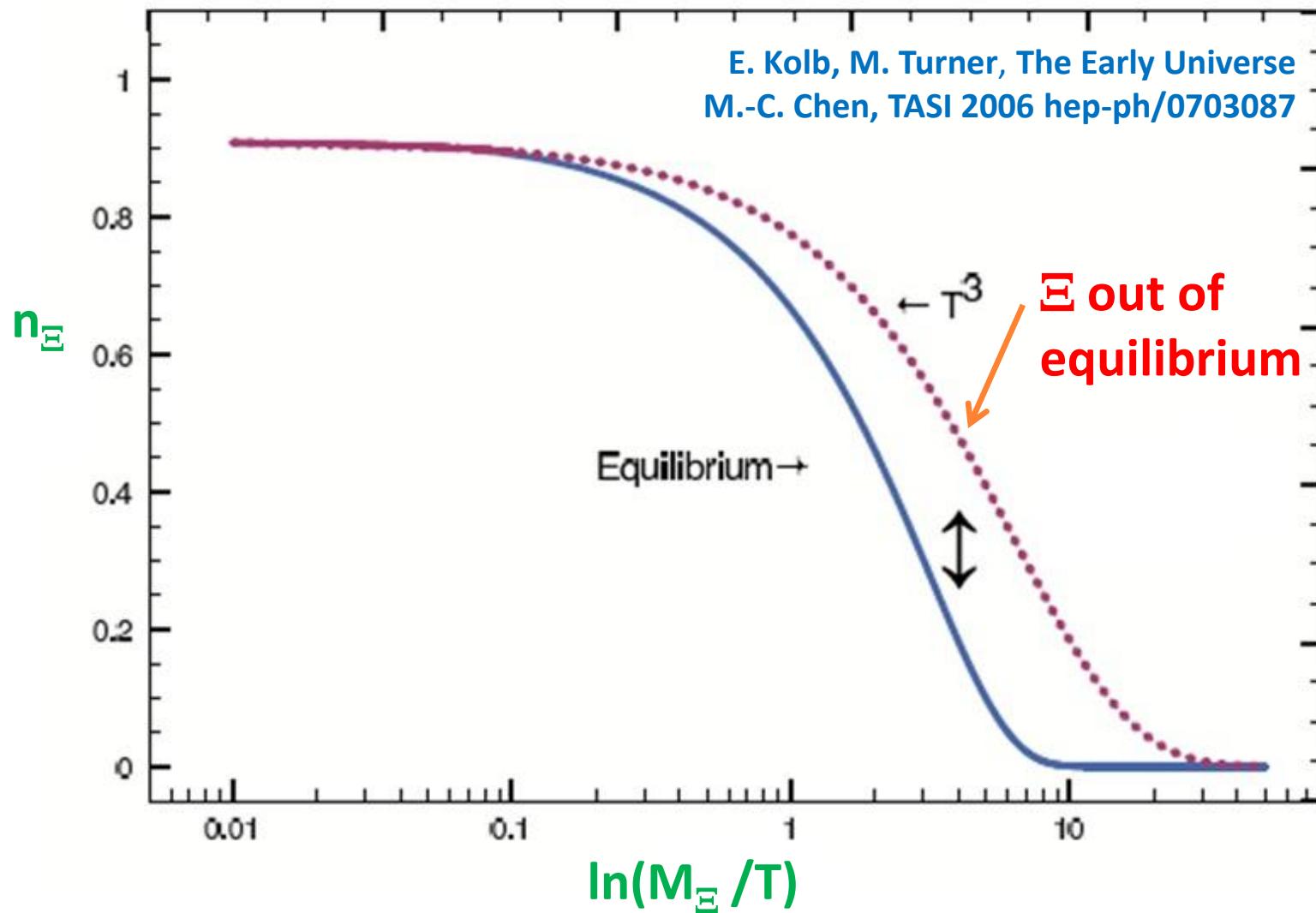
Dirac Leptogenesis

K. Dick, M. Linder, M. Ratz, D. Wright, PRL 84, 4039 (2000)

H. Murayama, A. Pierce, PRL 89, 271601 (2002)



Ξ Freeze out



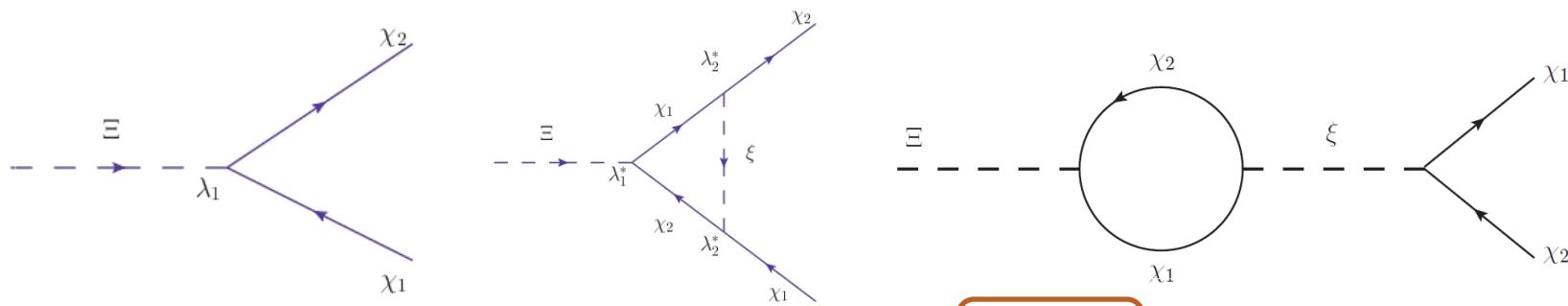
Baryon Number Asymmetry

M-C Chen, JH, W. Shepherd, JHEP 1211 (2012) 059

$$L \supset m_{\Xi}^2 |\Xi|^2 + m_{\xi}^2 |\xi|^2 + \lambda_1 \Xi \bar{\chi}_1 \chi_2 + \lambda_2 \xi \bar{\chi}_1 \bar{\chi}_2$$

Once Ξ out of equilibrium, χ_1, χ_2 further decay to leptons

Interference \longrightarrow CP Asymmetry



CP Asymmetry:

$$\varepsilon_{\Xi} = \frac{8 \operatorname{Im}[\lambda_1^2 \lambda_2^2] \operatorname{Im}[I_{\Xi\xi}]}{\Gamma_{\Xi}} \propto \lambda_2^2$$

B Asymmetry:

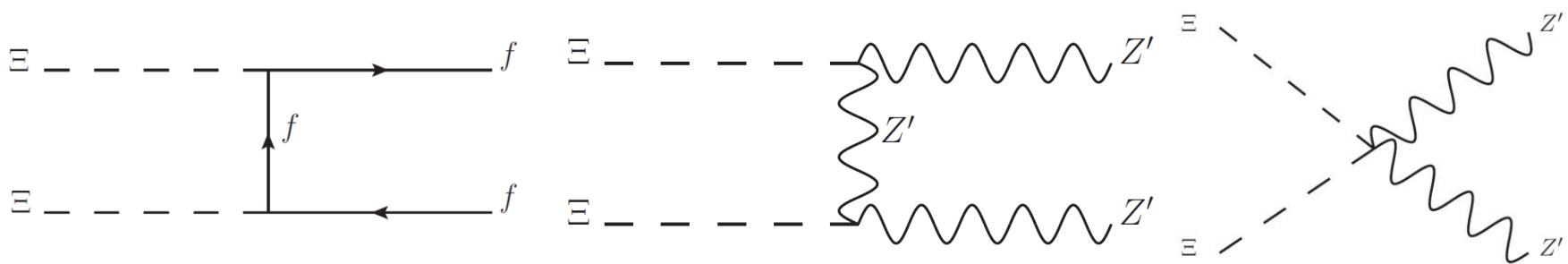
$$\eta_B \sim n_{\nu_R} \sim (\varepsilon_{\Xi} \boxed{\eta_{\Xi}} + \varepsilon_{\xi} \boxed{\eta_{\xi}})$$

Abundance

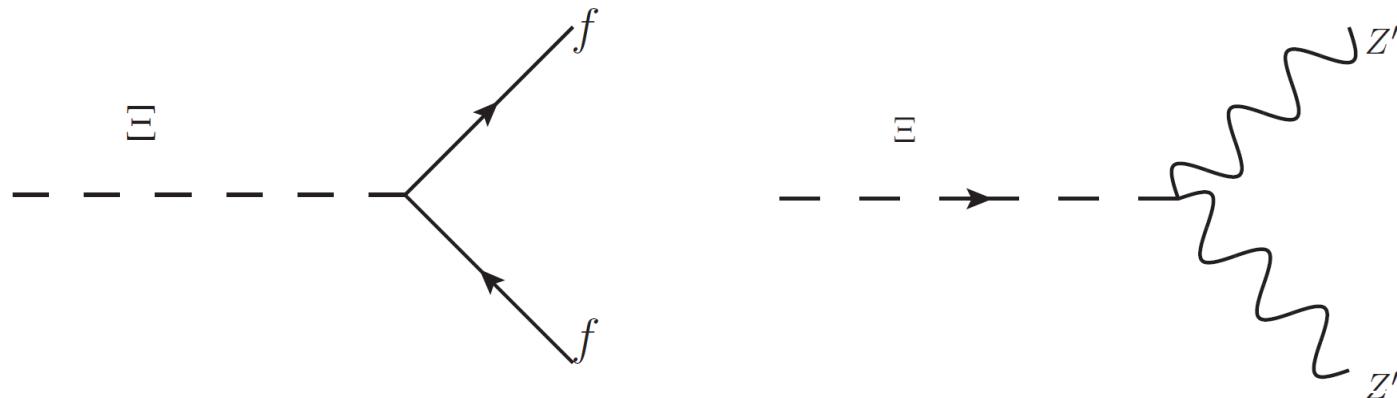
Wash Out Effects

M-C Chen, JH, W. Shepherd, JHEP 1211 (2012) 059

Annihilation:

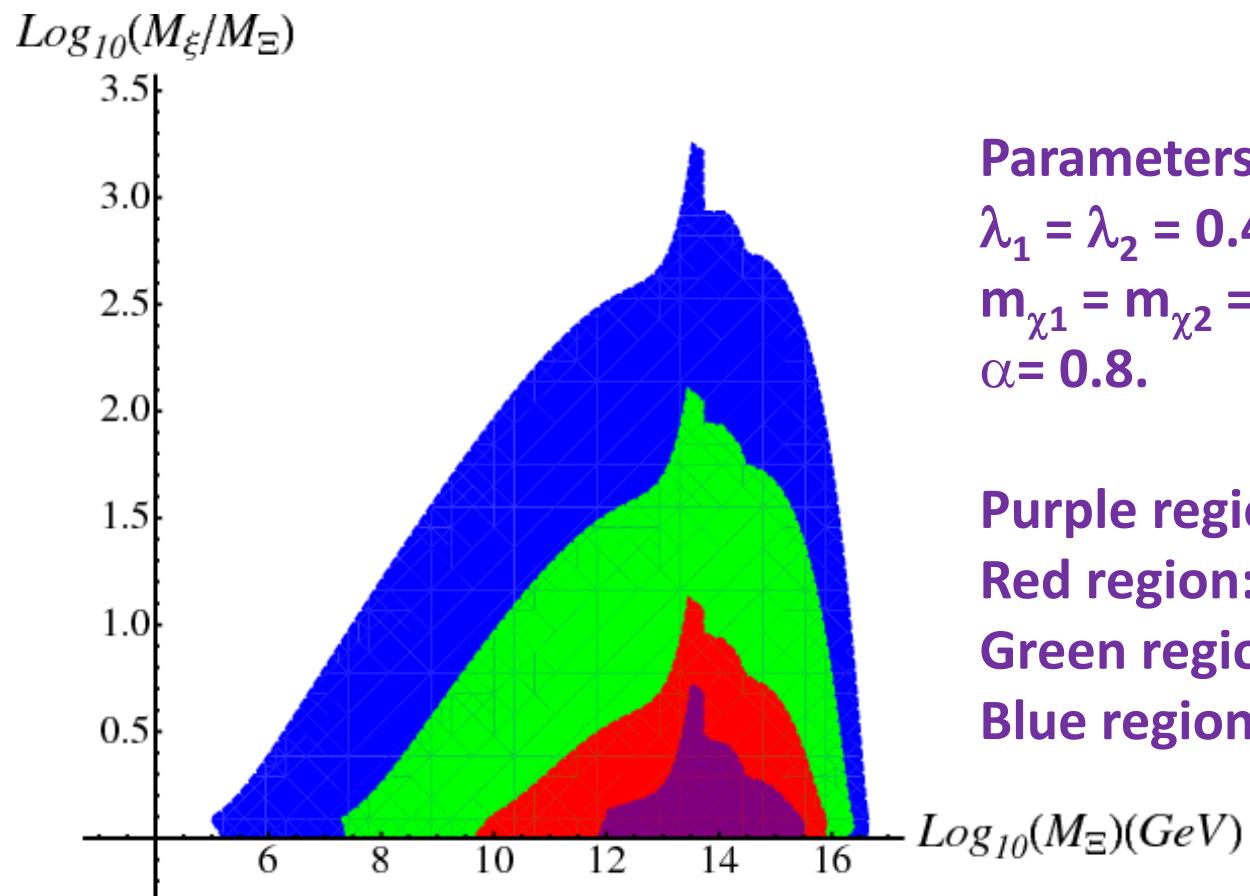


Inverse Decay:



Numerical Result

M-C Chen, JH, W. Shepherd, JHEP 1211 (2012) 059



Parameters:

$$\lambda_1 = \lambda_2 = 0.4 e^{-i\pi/8} ;$$

$$m_{\chi_1} = m_{\chi_2} = 0.4 m_\Xi ;$$

$$\alpha = 0.8 .$$

Purple region: $\eta_B \geq 6.19 \times 10^{-5}$

Red region: $\eta_B \geq 6.19 \times 10^{-6}$

Green region: $\eta_B \geq 6.19 \times 10^{-8}$

Blue region: $\eta_B \geq 6.19 \times 10^{-10}$

Conclusion

- The Dark 3+1+1 model can accommodate with the LSND, MiniBoone sterile neutrino exps.
Anomaly
- It can satisfy various cosmology, collider, muon decay constraints etc.
- MeV scalar can be the dark matter candidate to explain the 511keV INTEGRAL gamma line
- With additional $U(1)'$ family symmetry, all fermion masses and mixings can be generated naturally
- Realistic Dirac leptogenesis can be realized



Back Up

Parameter Counting

| A/P | | LBL approx. | (A/P) | SBL approx. | (A/P) |
|-----|-----|--|-------|--|-------|
| 3+2 | 9/5 | $V_{35}V_{34}V_{25}O_{24}O_{23}O_{15}O_{14}V_{13}$ | (8/4) | $V_{35}O_{34}V_{25}O_{24}O_{15}O_{14}$ | (6/2) |
| 3+1 | 6/3 | $V_{34}O_{24}O_{23}O_{14}V_{13}$ | (5/2) | $O_{34}O_{24}O_{14}$ | (3/0) |

Parameters of Neutrino Exps.

| Experiment | mode | # points | Distance (m) | E | Δm^2 (eV 2) |
|------------|--------------------------|-----------------|------------------|------------------------|-------------------------|
| MB | $\bar{\nu}_\mu, \nu_\mu$ | 11×2 | 541 | 200 – 3000 MeV | $\gtrsim 0.1$ |
| LSND | $\bar{\nu}_\mu$ | 8 | 29.8 | 10 – 60 MeV | $\gtrsim 0.3$ |
| KARMEN | $\bar{\nu}_\mu$ | 1 | 17.7 | 1 – 50 MeV | $\gtrsim 1$ |
| E776 | $\bar{\nu}_\mu, \nu_\mu$ | 1 | 1000 | 1 – 10 GeV | $\gtrsim 1$ |
| NOMAD | ν_μ | 1 | 625 | $\gtrsim 10 - 200$ GeV | $\gtrsim 10$ |
| NuTeV | $\bar{\nu}_\mu, \nu_\mu$ | 1 | 1436 | $\gtrsim 10 - 300$ GeV | $\gtrsim 10^2$ |
| CCFR | ν_μ | 1 | 1436 | $\gtrsim 10 - 300$ GeV | $\gtrsim 10^2$ |
| TOTAL | $\bar{\nu}_\mu, \nu_\mu$ | 30 pos., 5 null | $\sim 10 - 1436$ | 10 MeV – 600 GeV | $\gtrsim 0.1$ |

| Experiment | mode | # points | Distance (m) | E | Δm^2 (eV 2) |
|-----------------------|------------------------|----------|--------------|-----------------|-------------------------|
| CCFR | ν_μ | 1 | 714 and 1116 | 40 – 200 GeV | $10 - 10^3$ |
| CDHS | ν_μ | 1 | 130 and 885 | 2 – 6 GeV | $10^{-1} - 10$ |
| Mention <i>et al.</i> | $\bar{\nu}_e$ | 21 | 9 – 1050 | ~ 3 MeV | $10^{-2} - 10^{-1}$ |
| Bugey 40/15 ratio | $\bar{\nu}_e$ | 25 | 15 and 40 | 3 – 8 MeV | $\gtrsim 10^{-2}$ |
| TOTAL | $\bar{\nu}_e, \nu_\mu$ | 48 | $10 - 10^3$ | 3 MeV – 200 GeV | $10^{-4} - 10^3$ |

CKM Matrix

Definition:

$$L_{Yukawa} = Y^u Q \bar{u} H_u + Y^d Q \bar{d} H_d$$

$$M_{diag}^f = V_L^f Y^f V_R^{f+} (\nu/\sqrt{2}) (f = u, d) \quad V_{CKM} = V_L^u V_L^{d+}$$

Standard Parameterization:

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix}$$

$$c_{ij} = \cos \theta_{ij}, s_{ij} = \sin \theta_{ij} \quad \theta_{ij}: \text{Mixing angle}; \quad \delta_{13}: \text{CP-violating phase}$$

Experimental Results:

$$\sin \theta_{12} = 0.2255 \pm 0.0006; \quad \sin \theta_{23} = (4.115 \pm 0.045) \times 10^{-2};$$

$$\sin \theta_{13} = (3.61 \pm 0.12) \times 10^{-3}; \quad \delta_{13} = (69.9 \pm 3.0)^\circ$$

UTfit 2010

PMNS Matrix

Definition:

$$L_{Yukawa} = Y^e L \bar{e} H_d + Y^\nu L \bar{\nu} H_u + M_{RR} \nu \bar{\nu} + \frac{Y^{LL}}{\Lambda} LL H_u H_u$$
$$M_{diag}^f = V_L^f M_{eff}^f V_R^{f+} (f = \nu, e) \quad U_{PMNS} = V_L^{\nu+} V_L^e$$

Standard Parameterization:

$$U_{PMNS} = V \times diag(1, e^{i\frac{\alpha_{21}}{2}}, e^{i\frac{\alpha_{31}}{2}})$$

α_{21} α_{31} : Majorana CP-violating phase

Experimental Results:

G. Fogli et al., PRD84, 053007(2011)

$$\sin^2 \theta_{12} = 0.306^{+0.018}_{-0.015}; \quad \sin^2 \theta_{23} = 0.42^{+0.08}_{-0.03}; \quad \sin^2 \theta_{13} = 0.021^{+0.007}_{-0.008}$$

Large θ_{13} :

T2K, Double Chooz, Daya Bay, etc indicate non-zero θ_{13} ,

$$\sin^2 2\theta_{13} = 0.092 \pm 0.016(stat) \pm 0.005(syst) \quad \text{Daya Bay @ } 5.2\sigma$$